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Non-destructive Testing with FWD on Whole and Broken AC Pavements

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Abstract:

Extensive testing of flexible pavements with the Falling Weight Deflectometer (FWD), on various test sites in Ontario, has aided the development of a rational method of deflection basin interpretation. The goal is an updated version of the author's PROBE program, which calculates important mechanistic response parameters (as before), and determines the quality of data and the degree of structural integrity of the pavement layers.

Using the theory of Boussinesq and Odemark's method of equivalent layer thickness, two quantities are defined in order to help interpret deflection bowl data:

(1) the effective modulus of measured surface deflection, and
(2) the effective modulus of subgrade deflection.

Both moduli change with their radial distance from the test load. When plotted they may briefly be referred to as (1) the effective modulus profile, and (2) the subgrade modulus profile, respectively. Both moduli provide apparent values of elastic stiffnesses, using uniform elastic half-space solutions. They are parameters for a systematic study of the difference between the theoretically expected and the actually observed behaviour of AC pavements.

The effective modulus profile (1) serves mainly to evaluate the strength, quality and integrity of pavement layers. The subgrade modulus profile (2) is used mainly to estimate the subgrade modulus at and near the test load, which is the basis for further calculations of primary response parameters by the Odemark method. Examples are presented, ranging from very good to poor, and broken conditions.

Computer simulations with various programs suggest two major points:

1. Dynamic effects have only a comparatively minor influence, so that elastostatic modelling appears to be feasible.
2. Deflections may die away faster with radial distance than expected, due to an increase of the subgrade modulus with depth and/or the unrecorded presence of a bedrock face.

In short, the new approach tries to obtain information and interpretations on system features of field cases by systematically studying the deviation from simple elastostatic modelling.

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Executive Summary

Pavements: distress observation versus non-destructive testing

Asphalt concrete (AC) pavements are first built, and then they wear or deteriorate under heavy traffic loads and environmental forces. They are repaired, rehabilitated, or reconstructed when their deterioration has become intolerable. The rational approach of monitoring, planning, and funding this cyclical process is called "pavement management", which is a rational approach to assure getting "the biggest bang for the buck".

The observation of pavement distress is happening on the surface, and little can be ascertained about the conditions underneath, except for a few clues in terms of deformations and patterns of cracks. Most technically advanced highway agencies want to learn more about the quality and strength of their pavements, usually their biggest investment, and have opted now for a method of non-destructive testing in the form of the Falling Weight Deflectometer (FWD).

The Falling Weight Deflectometer is fast and reliable, but . .

The FWD is essentially a machine which drops a weight on the pavement in a controlled manner. A set of transducers at various distances from the falling weight measures the time-trace of the resulting wave of deflections. The pressure or load at the point of impact is monitored by a load cell. The propagating peaks of the deflection wave at various radial distances resemble a deflection bowl created by a load from a single tire of a heavy vehicle. The measurements are accurate, fast, and reliable, contrary to the Benkelman Beam which has become an instrument of the past.

Unfortunately, in spite of years of effort in the US and elsewhere, the success of the FWD in accurately measuring pavement deflections has not been matched by providing a fast and reliable computer program which could process and interpret the measured deflection values. With numerous experts working on this problem for several decades, the reason is probably the inherent difficulties of modelling the complex materials of pavement layers.

Gradually it has become clear that pavement materials defy all mathematical modelling by even the most advanced theories of visco-elasticity and dynamics. But even if advanced theories were to succeed in describing the behavior of pavement materials in FWD tests, the resulting computer program would be impracticable for processing large amounts of raw data, such as the data now being collected by the Strategic Highway Research Program in the US and Canada.

The new approach: studying the difference between theoretical and actual behavior of material

When nature defies accurate description by a mathematical theory, it is still possible to obtain information by studying the deviation of nature's behavior from such theories. For instance, in the theory of population growth, one would expect an exponential increase with time, (in a culture of germs, for instance), provided that food supplies are unlimited. When the mathematically defined growth curve suddenly bends down, away from its expected exponential shape, one can deduct the important information that food supply in the observed population has indeed become scarce.

This is an analogy which can be applied to pavements: On the one hand, the FWD instrument measures the deflections on an actual pavement composed of layers of asphaltic concrete and granular bases. On the other hand, there are simple mathematical models which describe the vertical deflections on the surface of a uniform elastic half-space. For the same load, one can compare the measured deflections with the expected theoretical ones. A simple parameter of comparison can be derived: the "effective modulus of measured surface deflection".

This modulus is the elastic stiffness that a uniform half-space would have, at the same radial distance and for the same surface deflection as the one measured by FWD. The modulus varies with radial distance from the load axis and can be plotted accordingly. Much information can be obtained from studying profiles of this "effective modulus of measured surface deflection". (The same concept was introduced earlier by Ullidtz under the name "surface modulus".) For a concentrated load, L, the effective modulus of surface deflection is (after Boussinesq, not too close to the load):

$$E_x = \frac{L(1-\mu^2)}{\pi XY}$$

where E_x = effective modulus of surface deflection, in MPa

L = test load, in Newton

X = radial distance, in mm

Y = measured FWD deflection, in mm

μ = Poisson's ratio

To obtain E_x values close to and at the test load, Equation E-1 is used in a somewhat extended form.

Cracking the oyster of subgrade modulus (E_m)

In order to compute subgrade stresses and/or strains under the load, even by the simplest available method (Odemark), it is important to have an approximate value for the elastic stiffness of the subgrade, the subgrade modulus. A value is needed which is valid in the vicinity of the load.

Thus, it was necessary to expand the aforementioned idea, in order to obtain more information on the subgrade modulus, and the principle of studying a modulus parameter has been extended to the vertical deflections on top of the subgrade.

To establish a profile of the "effective modulus of subgrade deflection" is more difficult, because these deflections are not immediately known through FWD measurements. But they can be estimated from the measured surface deflections. However, the difficulty is compounded by the fact that this modulus parameter is also dependent on the effective depth of the layers above the subgrade surface, and the modulus profile must be established within a procedure of iterative backcalculation, for which the simple method of equivalent thickness (Odemark) can be used.

Many profiles of the effective modulus of subgrade deflection were studied. In the vicinity of the test load, the profiles exhibited a surprising variety and variability. Depending on the state of layer materials, the profiles changed from almost straight lines (for elastic continua), to curves with moderate or steep gradients, for AC pavements in good or bad condition, respectively. From studying many cases, conclusions were drawn for estimates of the elastic stiffness in the subgrade, to be used for calculating stresses and strains, refer to Table E-1.

The new PROBE program "probes" also for quality of data and material

Through curve-fitting of the deflections or the corresponding effective modulus profiles, it is possible to evaluate the quality of measured deflection data. A lack of quality of such data usually indicates an advanced state of pavement deterioration. Interpretation of FWD data should not be attempted by staff with insufficient experience.

The current work on FWD with its new approach may constitute the first step towards using FWD technology in highway design, in a practical manner.

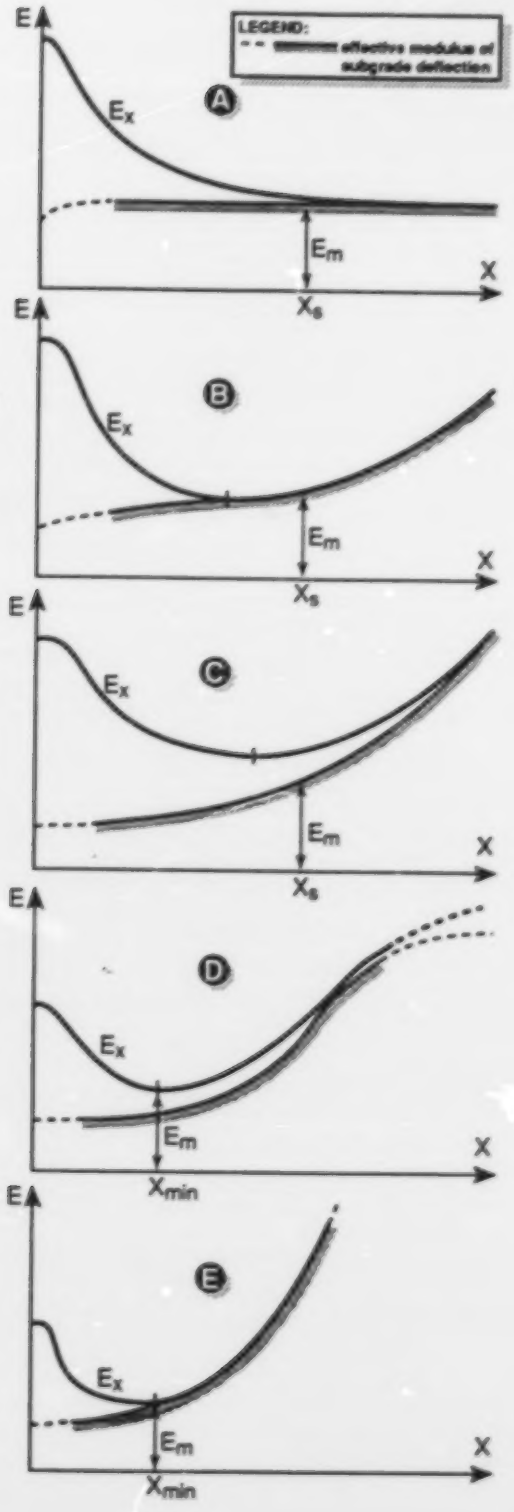

Table E-1/ Characteristics of effective moduli profiles

A is an idealized case of a layered pavement structure with linear elastic materials, with input deflections computed by a continuum solution of elastic layer theory, the ELSYM5 program. The profile of the effective modulus of subgrade deflection is a horizontal straight line, located underneath the effective modulus profile of surface deflections, E_x, and approaching it asymptotically at large radial distances. It represents, in this case, the constant subgrade modulus, except for a quasi-singularity disturbance close to the load where the line bends down.

B is the same artificial case, modified by replacing the "infinite" subgrade thickness by a finite one. The resulting plot exhibits a rising curve of effective modulus of subgrade deflection.

C : Using data from an actual FWD test on an AC pavement in good condition, the subgrade modulus profile, is also a rising curve, but of a different character than in B, above.

D and E: Using data from AC pavements in poor (D) and very poor (E) condition, the subgrade modulus profile becomes more curved and steeper. This might be the effect of increasng discontinuity of layer materials with regard to horizontal wave propagation and shear load transfer. The minimum value of E_x decreases and moves closer to the point of origin (load axis).

1/ Introduction

Owing to the popular use of the Falling Weight Deflectometer (FWD), a great deal of effort has gone into the interpretation of FWD-generated deflection data. Such efforts have mainly centred around the "backcalculation" of layer material properties within the framework of continuum mechanics, in particular, the elastic layer theory.

This theory, however, implies that the pavement layers are not broken or cracked, or that the FWD test is carried out on a spot of unbroken or uncracked pavement. Continuum mechanics does not describe cracked or broken pavements, and this has diminished the usefulness of backcalculated results.

Up to this time, the author's PROBE program was subject to the same limitations. Many tests in Ontario have been carried out on flexible pavements which were severely cracked or broken, and it was found that the original PROBE program (as any other elastostatic analysis method) could not be used to interpret the results.

Such experience with respect to analyzing data, gathered at severely damaged sections has confirmed the inappropriateness of using elastic theories in the usual way. Therefore, an alternative backcalculation methodology has been investigated. Rather than emphasizing more realistic modelling of the boundary value problem, the new approach, incorporated into the PROBE program, uses differences between the "real" problem and the "idealized" problem, in order to estimate a weighted average of in-situ properties and to obtain other information on the state of materials.

2/ The Effective Modulus of Measured Surface Deflection

The Falling Weight Deflectometer is an instrument which measures the peaks of a deflection wave from an impulse load created by a falling weight. The test load is distributed over a circular contact pressure area of 30 cm in diameter and thus resembles (also in its duration in time, i.e. its time-trace) a passing heavy single-tire wheel load from a truck. An essential feature is that the peak deflections, measured at various distances from the load, superficially resemble those corresponding to an elastostatic load.

The first step of the new approach is to assume that the FWD-generated deflections correspond to elastostatic deflections on a uniform elastic half-space. Then, in order to interpret the data, "effective moduli" are calculated.

Definition: The "effective modulus of measured surface deflection" of a flexible pavement in an FWD test is defined as follows: it is the modulus which a uniform elastic half-space would have under a corresponding static load, having the same deflection as measured by the FWD sensor, at the same distance from the load axis on the flexible pavement. This term is sometimes called the "effective modulus" or "surface modulus". It is a function of the distance from the load axis.

Derivation: The concept is derived from [1] which contains an equation for the vertical deflections in a uniform elastic halfspace, loaded by a circularly distributed load. For the surface deflections (Z = 0), the equation can be written as follows:

$$Y = P\left(1 - \mu^2\right) A H/E \qquad (1)$$

where
- Y = vertical surface deflection
- P = contact pressure, force per unit area
- μ = Poisson's ratio (assumed to be 0.35)
- A = radius of loaded area
- E = the modulus of the linearly elastic material
- H = a function of the ratio X/A
- X = distance from the load axis

Solving Equation (1) for E, one obtains the function of the "effective modulus of surface deflection", E_X, in which the deflections, Y, are now regarded as the result of FWD deflection measurements.

$$E_X = P\,(1-\mu^2)\,A\,H\,/\,Y \qquad (2)$$

Note that, for distant deflections (X > 5A) the factor, H, merges into H = A/X . This means Equation (1) becomes identical to the Boussinesq equation for a concentrated load, L (with $L = \pi\ P\ A^2$), and Equation (2) is then identical to the one offered by Ullidtz under the name "surface modulus" [2].

2.1/ Characteristics of the Effective Modulus Profile

Such features are illustrated in Figures 1 to 6, which were drawn after studying many field tests of flexible pavements in Ontario. The following characteristics have been observed:

1) Near the load, the stiffening effect of the upper structural layers is strongest, and the effective modulus is large, since at and around the load position the effective modulus represents the over-all stiffness of all the pavement layers.

2) When using computer-generated data (ELSYM5), on a layered pavement system of linearly elastic materials and "infinitely" deep subgrade with constant elastic stiffness, the distant tail of the effective modulus profile merges into a *horizontal* asymptote at the level of the subgrade modulus, E_m, as shown in Figure 1. The distance of the asympote from the X-axis represents the subgrade modulus, E_m.

3) When using real data from the tested flexible pavements, this asymptote becomes a line or curve with a *positive gradient*, as illustrated in Figures 2 to 5. The reason is that the measured deflections die away faster with increasing distance than the elastostatic model would allow. A faster decrease in deflections means an increase in the computed "effective modulus" values.

4) Because of the characteristics described under 1) and 3), on all pavements tested in the field, the profile of the "effective modulus of surface deflection" has a minimum, usually not too far from the load (within about a metre or less). The location of the minimum signifies that the stiffening effect of the upper layers has faded away, and the stiffness at and beyond this distance is determined by the subgrade.

5) Observations on field data show that both, the *magnitude* of this minimum value of the effective modulus and its *distance* from the load axis, diminish with a decrease in pavement integrity or wholeness (usually manifested by cracks).

6) On flexible pavements of good or fair condition (Figures 2, 3, and 5), the distant values of the effective moduli are located on a line or curve which can be called the "tail modulus function". On pavements in severely cracked or broken condition, the tail modulus function cannot be determined (Figure 4).

2.2/ Quality Indicators from Curve-Fitting of the Tail Modulus Function

The *tail modulus function*, E_{mx}, is derived by modifying Equation (8) from [3]:

$$E_{mx} = \frac{P A^2 (1-\mu^2) X^{(\eta-1)}}{\zeta} \qquad (3)$$

where
- E_{mx} = tail modulus function, as established below
- P = contact pressure, force per unit area
- A = radius of contact pressure area
- μ = Poisson's ratio (0.35)
- X = distance from the load
- η, ζ = constants found by curve-fitting deflection data

With $X = X_t$, the "toggling point distance", Equation (3) represents the subgrade modulus, E_m, of the original PROBE program, after the constants η and ζ have been found by curve-fitting the distant deflections.

With X being a variable, Equation (3) is now referred to as the "tail modulus function". It is related to the hyperbola used to curve-fit the measured FWD deflections, Y, namely, Equation (7) in [3]:

$$Y = \frac{\zeta}{X^{\eta}} \qquad (4)$$

In the earlier version of PROBE, based on consistency tests on data collected in Ontario, [3, 4], the value of the tail modulus function at X_t (= 0.75 m) was considered an approximation of the subgrade modulus, E_m, valid at and around the test load. This approximation yielded consistent results on various test sections in Ontario.

Further, the modulus, E_m as calculated by the original PROBE program (Equations (3) and (4) with X_t = 0.75) compares well with the subgrade modulus computed by the MODULUS program [5]. The comparison is illustrated in Figure 7. The values E_4, from the MODULUS program, are approximately 10% to 25% larger than the values E_m. The correlation coefficient of the linear regression analysis for 21 reliable data points (out of 25) is r = 0.984.

In the current version of PROBE, the tail modulus function is used only to determine the quality of flexible pavements. The subgrade modulus is estimated by calculating an "effective modulus of

subgrade deflection" in the vicinity of the test load, at a depth corresponding to the equivalent thickness of the pavement layers.

The tail modulus function is established practically by curve-fitting the last three or four values of the effective modulus of measured surface deflection, E_x. For $X/A > 5$, this effective modulus is in the Boussinesq range of Equation (2):

$$E_x = \frac{P(1-\mu^2)A^2}{XY} \tag{5}$$

where: A = radius of contact pressure area
P = contact pressure of test load, force per unit area
μ = Poisson's ratio
X = distance of sensors from load axis
Y = measured deflections at distance X

Because of Equations (3) and (4), the curve-fitting is carried out by linear regression analysis of the logarithms:

$$\log E_{mx} = \log C + (\eta - 1) \log X \tag{6}$$

To establish the constants, C and η, with some confidence, three or four valid points from the tail of the deflection basin are needed.

In the current version of the PROBE program, poor pavement quality beyond the location of the minimum value of the effective modulus of measured surface deflection is indicated by a relatively low value of the correlation coefficient. Excessively high values of η (> 2.5) are also indicative of poor quality of the pavement (cracked or broken AC layers).

3/ Effective Modulus of Subgrade Deflection

The definition of the term "effective modulus of subgrade deflection" is similar to that given prior to Equation (1), but now pertains to the vertical deflection on top of the subgrade. It is calculated by Boussinesq's equation for vertical deflections in a uniform half-space, at the depth $Z = H_{em}$.

$$E_{mz} = \frac{P(1-\mu^2)A^2}{XY_s}\left[\frac{1}{\sqrt{1+\left(\frac{Z}{X}\right)^2}} + \frac{\left(\frac{Z}{X}\right)^2}{2(1-\mu)\left(\sqrt{1+\left(\frac{Z}{X}\right)^2}\right)^3}\right] \quad (7)$$

where E_{mz} = subgrade modulus function or profile, effective modulus of subgrade deflection
$Z = H_{em}$ = sum of the equivalent layer thicknesses, with respect to the subgrade modulus
Y_s = vertical deflection on top of the subgrade, refer to Equation (8)
X = radial distance from the load axis
P = contact pressure of loaded area
A = radius of loaded area
μ = Poisson's ratio

Equation (8) is an approximate correction for establishing the deflection on top of the subgrade, Y_s. The value Y_s (unknown) is computed from the measured surface deflection, Y:

$$Y_s = Y\left[1-(1-K)\cdot\frac{E_m}{E_{1eff}}\cdot\frac{H_1+H_2+H_3}{Z}\right] \quad (8)$$

where K = the factor in the square bracket of Equation (7)
E_m = subgrade modulus
E_{1eff} = combined effective modulus of upper layers
$H_1+H_2+H_3$ = sum of thicknesses of upper layer

Note that the surface and subgrade modulus functions, represented by Equations (2) and (7), respectively, virtually merge at large radial distances. As shown in Table 1, Equations (3) and (7) provide similar moduli at $X_t = 0.75$ m, at approximately $H_{em} = 1$ m.

Table 1/ Comparison of E_m (Equation 3) and E_{mz} Equation 7)

File	H_{em} (based on E_{mz})	E_m, Mpa	E_{mz}, MPa	% Difference
S139	1.353 m	148.6	131.7	-13.0 %
S231	0.861 m	107.8	132.5	23.0 %
TP-0	1.081 m	122.8	105.4	-16.5 %
HAG60	1.027 m	248.5	223.8	-11.0 %

File information (refer also to examples in [4])

S139:	Early test on the Highway 7N test site, strongest Section A
S231:	As before, weaker Section B (Example 2, [4])
TP-O:	Test pit location, C-SHRP section near Sarnia, before overlay
HAG60:	Old pavement near Hagersville, Highway 8 (Example 4, [4])

In cracked or broken pavements, the minimum value of the effective modulus profile decreases.

When the pavement is very severely cracked and completely broken, this minimum must finally approach a value which represents the subgrade modulus, i.e. the modulus near the top of the subgrade at and around the test load.

3.1/ Calibration on Hwy 7N, Test Sections A and B

Equation (7) is used by the current PROBE program to calculate the effective modulus of subgrade deflection, and it must do so within the process of iteration of the backcalculation procedure. At each step of iteration, there is a slight change in E_m and H_{em}, until the deflections match. The subgrade modulus profiles in Figures 8 to 12 were calculated in this way.

The old PROBE version used the tail modulus function to estimate E_m at a selected distance X_t = 0.75 m. This value was found by establishing consistency between the 1987 Fall FWD tests, on neighboring Points of Sections A and B, on Highway 7N, stipulating that the subgrade modulus must be equal in both sections, except for statistical scattering. The sections differed in their design strength.

The new PROBE version uses the subgrade modulus profile instead. The same procedure leads to about the same radial distance of X_s = 0.75 m, working over the same test data as before.

As an example of X_s-calibration, adjacent data on Lane 3 of the Highway 7N test sections, A and B, are shown in Table 2, based on data from Fall 1987. The result is: a selected radial distance of X_s = 0.75 m leads to about *the same* average subgrade modulus in both sections of *different* structural strength (H_{em}).

Table 2/ Calibration of X_S on Highway 7N

Section A (strong design)			Section B (weak design)			
File	H_{em}	E_m	file	H_{em}	E_m	X_s
	m	MPa		m	MPa m	
S139	1.358	131.65	S230	0.896	135.77	0.75
S138	1.410	124.57	S231	0.861	132.45	0.75
S137	1.220	149.63	S232	0.859	136.51	0.75
S136	1.317	119.57	S233	0.997	123.77	0.75
S135	1.130	135.10	S234	0.901	144.93	0.75

Average of Sec. A: 132 MPa Average of Sec. B: 135 MPa

The average value of the subgrade modulus in Section B is 2% larger than in Section A. The difference is insignificant.

The result of the X_S calibration is similar to that of the original "toggling point distance" of X_t = 0.75 m. The moduli are often somewhat different from those computed by the original PROBE program.

The calibration determines an "in-situ" average modulus, which was valid at least for the subgrade at the Highway 7N test site in Fall 1987. The term average is used with regard to the fact that the local subgrade modulus increases with the depth from the surface.

4/ Discussion on the Effective Modulus Profiles

4.1/ Characteristics of the Effective Modulus of Subgrade Deflection

Again, one may start the discussion with an idealized case of a layered pavement structure with linear elastic materials, with input deflections computed by a continuum solution of elastic layer theory, the ELSYM5 program. The result is plotted in Figure 8. The effective subgrade modulus profile is virtually a horizontal straight line, similar to the tail modulus function shown in Figure 1, located underneath the effective modulus profile of measured surface deflections and approaching it asymptotically at large radial distances. It represents the constant subgrade modulus, except for a quasi-singularity disturbance close to the load where the line bends down.

Next, the artificial case is modified by replacing the infinite subgrade thickness by a finite one. The resulting plot, Figure 9, exhibits a rising curve of effective modulus of subgrade deflection.

Using data from an actual FWD test on an AC pavement in good condition (File S139), the subgrade modulus profile, Figure 10, is also a rising curve, but of a different character than in Figure 9.

Using data from AC pavements in poor condition (Files S334 and S434), the subgrade modulus profile becomes more curved and steeper, refer to Figures 11 and 12. This is possibly the effect of increasing discontinuity of layer materials with regard to horizontal wave propagation and shear load transfer.

The different character of the subgrade modulus profile curves in Figures 9 on the one hand, and Figures 10, 11, 12 on the other hand, may be due to the fact that Figure 9 represents a theoretical case. However, the cause may also be that the assumed and real-live materials differ in their character, in terms of continuum versus (bonded or non-bonded) discrete elements.

5/ Understanding the Field Data: Computer Simulations

The increase of the effective modulus profile at distances from the load beyond the minimum value is concordant with the exponent, η, being larger than one, observed on all flexible pavements tested. Even values of η larger than two were measured on the test section, Highway 7N, Toronto Bypass. Computer simulations are helpful in understanding this effect.

As indicated previously, a comparison of effective modulus profiles, using data from computer-generated and measured deflection bowls, clearly indicates that differences exist between actual field conditions and what is assumed for modelling. In order to investigate possible reasons for the observed differences, an idealized two-layer pavement was studied, taking into account the effects of bedrock location and impact loading. The problem case consisted of a 15 cm thick plate with an elastic modulus of 2250 MPa and a Poisson's ratio of 0.35, supported by a homogenous subgrade with a modulus of 45 Mpa and a Poisson's ration of 0.50.

The deflection bowls were generated using the Bessel Fourier Series approach [6, 7] assuming a peak load uniformly distributed over a 15 cm radius base plate. For the dynamic analysis, the impact load was applied as a half sine wave over a time interval of 0.025 seconds, and a unit weight of 20 kN/m^3 was assumed.

Figure 13 provides a comparison of effective modulus profiles which were calculated using the generated deflection data, for various depths, D, of subgrade. As expected, the effective modulus for

the elastostatic case, where the subgrade extends to infinity ($D \rightarrow \infty$) approaches 45 MPa as the radial distance from the load gets larger.

The dip below 45 MPa and the subsequent small gradual increase in effective modulus is due to the Poisson's ratio of the plate being different from that of the subgrade. For the elastodynamic case ($D \rightarrow \infty$), the effective modulus continuously decreases. This is not surprising, since the decay rate of surface wave amplitude for the semi-infinite half-space problem is known to be less than that of an elastostatic deflection bowl.

Figure 13 suggests that the increase in effective modulus observed when using real data can possibly be attributed to the presence of bedrock. The strength of the effective modulus increase with depth depends on the subgrade thickness (D). As D decreases, both, the minimum effective modulus and the rate of increase of the distant effective modulus increase. In the simulations, the distance at which the modulus is a minimum is approximately equal to the effective thickness of the pavement structure, i.e.

$$H_{em} \equiv H \sqrt[3]{\frac{E_1}{E_m}}$$

The evidence from the analysis of the real and idealized deflection bowls indicates that the interpretation of the effective modulus profiles, which provide hints to the deviation of assumed and actual behavior, can be used to evaluate the possible presence of unexpected features in material properties and/or dimensions, such as the presence of a bedrock face or harder layers of subgrade in its lower strata.

The presence of bedrock at finite distances below the pavement represents a sudden change in subgrade stiffness with depth. The increases in effective modulus at larger radial distances from the load (observed in the field) can also be explained by a more gradual increase in subgrade modulus with depth.

The surface deflections at larger distances from the load, used for the effective modulus calculations, are more sensitive to modulus increases with depth than those close to the load.

Close to the load, the observed deflections are largely due to subgrade deformations in the upper zone of the subgrade, whereas the surface deflections farther away are due to straining the deeper strata within the subgrade.

Based on the results from the two-layer problem, the effective modulus profile provides considerable information for characterizing a pavement structure, such as an estimate of subgrade modulus close to the load (close to E_{min} in broken pavements, smaller than E_{min} in whole pavements), strength of subgrade modulus increase with depth (as indicated by $\eta > 1$), and stiffness of the upper pavement layer structure as reflected by H_{em}.

The fact that the effect of the subgrade modulus increases with depth on the effective modulus profile is more important than the influence associated with the dynamic nature of FWD loading. Fortunately, these effects are small, provided that only deflections in the vicinity of the load (up to H_{em}) are used for backcalculation.

It is clear that the use of distant sensor readings can lead to considerable, non-conservative errors in the subgrade modulus prediction, if the increase in subgrade stiffness with depth and/or the presence of bedrock are not properly taken into account.

Other possible reasons for a steep positive gradient of the effective modulus profile at distant radii, not studied by the computer simulation, is the discontinuity and/or anisotropy of granular or AC-layer materials as they are composed of bonded or unbonded discrete particles, [2]. This may also be presumed from the fact that, in Figures 9 versus Figures 10 to 12, the effective modulus curves of both the surface and subgrade deflection have different characteristics. In Figures 10 to 12, which pertain to the pavements with granular material, the steepness of the gradient begins closer to the load position and appears to grow with the magnitude and/or severity of cracks.

6/ The New PROBE Program

As before, the program processes FWD deflection data from a sequential input file. The file contains geometrical information such as the radius of load distribution, layer thicknesses, and distances of sensors from the load axis. Further, for any number of target load levels (usually four), the file must provide the readings of pressures of the load cell and the deflections at each of the transducers or "geophones", usually seven or more. The file contains also the mean temperature of the bitumen-bound layers, and a normal temperature and standard load level chosen by the user.

The deflections, pressures, and loads from each target load level (in the quasi-elastic range) are already processed within the file creation program to one normal or standard load level (usually 9000 lb or 40.034 kN), by adding the values and multiplying them by a factor. The PROBE program processes only values pertaining to the chosen standard test load level.
Two examples of PROBE results are presented in the form of printed output, on the following Tables 3 and 4. One is from a pavement of normal Ontario design (File S139) and the other from a deteriorated section scheduled to be rehabilitated by an overlay (File S434), Section D on Highway 7N, 1990 data. Table 3 and 4 correspond to the graphical representations in Figure 10 and Figure 12, respectively.

The PROBE version used in the examples (Tables 3 and 4) and in Figures 8 to 12 and 13, is based on the 2-layer solution of Kirk [8] for its backcalculation, matching maximum deflections under the test load only. Odemark's method of equivalent layer thicknesses was applied to obtain estimates of subgrade deflections, stresses, and strains. Horizontal strains at the bottom of the bitumen-bound layers were computed via curvature [3, 4]. Results are obtained within one minute on an ordinary PC.

The PROBE program implements a new approach which may still be subject to change.

Table 3/ Output example of AC - pavement in good condition File of PROB-Z Run, File A:S139 , Date: 08/07/91

Standard test load, in kN:	40.034	Radius, in mm: 150
Standard contact pressure, in kPa:	566.365	
Layer thicknesses, in mm:	140, 169, 513	
Total:	Z = 822 mm	
Temperatures, at test (and standard), in degrees Celsius:	8 (21)	
For Poisson's ratio = 0.50		
Maximum effective modulus, in MPa	517.02	
Minimum effective modulus, in MPa	136.76	at a distance of X = .64 m
For Poisson's ratio = 0.35		
Maximum effective modulus, in MPa	604.91	
Minimum effective modulus, in MPa	160.01	at a distance of X = .64 m
Structural Strength Index	SSI = 1.927	
First estimate of Em, in MPa	E = 128.0	

Distance	Deflection	Effective Moduli of Surface (2) and Subgrade Deflection		
m	mm	MPa (0.5)	MPa (0.35)	MPa (0.35)
0.00	0.24647	517.02	604.91	0.00
0.30	0.18657	176.51	206.52	79.95
0.60	0.11638	137.21	160.54	110.34
0.90	0.06838	155.31	181.71	156.68
1.20	0.03792	210.04	245.75	234.47
1.50	0.02380	267.71	313.22	312.90
1.80	0.01614	329.06	385.00	385.00

Correlation coefficient for distant effective modulus profile: 0.999865
Exponent, Eta = 2.0818*
AC-pavement condition under and near the end of the boom: very good

Exponent of close-distance subgrade modulus profile curve-fitting: 1.8
Average % error of fit: 0.082

Subgrade Modulus, in MPa : 131.7

E_{mr} beneath X_{min}, in MPa : 115.7
Equivalent thickness of structural layers, H_{em} = 1.503 metres

Primary Response Parameters: (Odemark method)	Unadjusted	Adjusted
Surface deflection under the load, in mm:	0.2465	0.2988
Tensile strain at AC bottom fibre (micro):	120.8	146.4
Radius of curvature under the load, in m:	579.66	478.21
Deflection of top of the subgrade, in mm:	0.1239	0.1353
Vertical compressive subgrade strain (micro):	114.2	137.8
Vertical compressive subgrade stress, in kPa:	15.0	18.1

* *rockbed depth at least 90 m*

Table 4/ Output example of AC-O pavement in bad condition Output File of PROB-Z Run, File A:S434, Date: 08/07/91

Standard test load, in kN: 40.034 Radius, in mm: 150
Standard contact pressure, in kPa: 566.365
Layer thicknesses, in mm: 90, 148, 290
Total: Z = 528 mm
Temperatures, at test (and standard), in degrees Celsius: 23 (21)

For Poisson's ratio = 0.50
Maximum effective modulus, in MPa 226.05
Minimum effective modulus, in MPa 88.56 at a distance of X = .38 m

For Poisson's ratio = 0.35
Maximum effective modulus, in MPa 264.48
Minimum effective modulus, in MPa 126.15 at a distance of X = .38 m

Structural Strength Index SSI = 1.000
First estimate of Em, in MPa E = 126.2

Distance	**Deflection**	**Effective Moduli of Surface (2) and Subgrade Deflection**		
m	mm	MPa (0.5)	MPa (0.35)	MPa (0.35)
0.00	0.56373	226.05	264.48	0.00
0.20	0.42933	117.48	137.45	81.13
0.60	0.12489	127.86	149.59	146.12
0.90	0.03724	285.12	333.59	333.59
1.20	0.01660	479.84	561.41	561.41
1.50	0.01336	476.93	558.01	558.01
1.80	0.01397	380.16	444.79	444.79

Correlation coefficient for distant effective modulus profile 0.864449
Exponent, Eta = 2.0949*

Exponent of close-distance subgrade modulus profile curve fitting: 3.3
Average % error of fit: 0.018

Subgrade Modulus, in MPa: 126.150

E_{mz} beneath X_{min}, in MPa: 94.125
Equivalent thickness of structural layers, H_{em} = 0.700 metres

Primary Response Parameters: (Odemark method)	**Unadjusted**	**Adjusted**
Surface deflection under the load, in mm:	0.56370	0.55222
Tensile strain at AC bottom fibre (micro):	328.7	322.0
Radius of curvature under the load, in m:	136.9	139.7
Deflection of top of the subgrade, in mm:	0.2702	0.2677
Vertical compressive subgrade strain (micro):	515.7	506.0
Vertical compressive subgrade stress, in kPa:	65.1	63.8

* *rockbed depth at least 90 m*

6.1/ Interpretation of the Example in Table 3, With Regard to Quality of Data

The Structural Strength Index (SSI) is approximately the ratio of the area under the effective modulus profile, E_x, of measured surface deflection from $X = 0$ to $X = X_{min}$, divided by the area E_{min} times X_{min}. By definition, it is a measure of the actual strength of the AC pavement in relation to the approximate subgrade strength, as represented by E_{min}. It is strictly established from the E_x profile only. The value of 1.927 in Table 3 indicates adequate design strength (i.e. no underdesign) without much deterioration. Weak or deteriorated designs are indicated by SSI values of less than about 1.6.

The subgrade modulus profile in the vicinity of the load position could be curve-fitted into a parabola of the form:

$$E = E_o + C X^e \qquad (9)$$

In the curve-fitting, the exponent, e, is used as a variable, together with E_o and C. It was found that the exponent, e, can serve as quality indicator of the pavement structure near the load. The very small average error of fit of 0.1 % is related to the increments of the exponent, i.e. steps of 0.1, used in an iterative procedure. For the three points used (i = 2, 3, and 4), infinitesimal steps would lead to error of fit 0%. The sensor points beyond one metre are ignored. A value of the exponent, e, below two, here 1.8, indicates a good structural integrity of upper layers, at and near the test load position.

With regard to the distant sensor positions beyond $X_{min} = 0.64$ m, the exponent, Eta, is not excessively high. The high correlation coefficient (> 0.995) of the last four points of the effective modulus of surface deflection indicates a very good condition of the AC pavement along the tail of the deflection basin.

6.2/ Interpretation of the Example in Table 4, With Regard to Quality of Data

Here the SSI value is not computed, but set by the computer to a low value of one, after the user has declared the pavement to be cracked or broken. The effect is that the subgrade modulus is assumed to be equal to E_{min}.

The curve-fitting of the subgrade modulus profile, of three points near the load, has resulted in an exponent of e = 3.3. This value is relatively high and is typical for severely deteriorated and/or broken structural layers of AC pavements. The exponent seems to grow with the increase in discontinuities of material with regard to the lateral transfer of shear stresses in the propagation of the impact waves in the FWD tests. The large exponent of 3.3 indicates a steep gradient of the

subgrade modulus profile, and the minimum effective modulus, 126.15 MPa was chosen to represent the subgrade modulus.

Tentatively, in cases of Ontario standard AC designs, it is suggested to use the coefficient, e, as a "Non-continuum - Lateral Discontinuity Index" (NLDI). Continuous elastic materials would exhibit low values, probably below one or even approaching zero. Unbroken AC pavements without cracks have shown moderate values of about two. Broken pavements have shown values up to four.

The curve-fitting of the last four points of the effective modulus of surface deflection resulted in a moderately high correlation coefficient of 0.864. However, this value is not high enough to declare the pavement along the tail as whole or unbroken, which would require a correlation coefficient of about 0.89 or larger.

Table 5/ List of parameters

Symbol	Name	Purpose
SSI	Structural Strength Index (tentative)	to identify underdesigned or otherwise weak pavements
E_{2seed}	First estimate of subgrade modulus	to provide seed value for back-calculation
COR	Correlation Coefficient	to evaluate quality of distant data and pavement condition
Eta	Exponent of distant deflection curve-fitting	to evaluate the deviation from the basic elastostatic model
NLDI	Non-continuum -Lateral Discontinuity Index (tentative)	to evaluate the degree of lateral discontinuity of AC designs
$E_{m_{av}}$	Subgrade Modulus, recommended in-situ average	to compute primary response parameters by Odemark method
E_{min}	Minimum value of effective surface modulus, E_x	to be used as subgrade modulus for cracked or broken pavements
$E_{mz,min}$	Effective subgrade modulus beneath E_{min}	to evaluate strength of design by comparing with E_{min}
X_s	Selected radial distance from load axis	to compute subgrade modulus for AC pavement in good or fair condition

7/ Consistency Check on Two Adjacent Points in Sections of Different Strength

Two points were selected, on the stronger Section A and on the weaker Section B of the Highway 7N test site, both in good condition.

The test was carried out on the neighbouring points on Lane 3, S139 and S230, in Sections A and B respectively, using Fall data of 1987. The results are plotted in Figure 14.

Sections A and B are of different strength, A being a normal standard design and B being deliberately underdesigned. In the effective modulus profiles (E_x) of surface deflection this difference in strength is reflected by the fact that the profiles *diverge* at and near the test load, the stronger section showing the larger values of E_x. This is well within what one might expect.

The consistency test is based on the assumption that the subgrade modulus at both locations must be the same, except for some insignificant difference from local fluctuations of material properties. If this is the case, then the two profiles of the effective modulus (E_{mz}) of subgrade deflection should not diverge, but must *converge* when approaching the load position. As illustrated in Figure 14, this is indeed the case. At small radial distances (below 0.75 m) the profiles of subgrade moduli (E_{mz}) are virtually the same.

An important conclusion can be drawn: On subgrades of the same stiffness (E_m), AC pavements have the same profile of effective subgrade modulus (E_{mz}) at and near the load (at least within X_{min}), independent from the strength of their upper layers. This opens up the possibility of treating subgrade modulus profiles statistically, on groups of points, even in sections of different strength.

8/ Conclusions And Recommendations

The need to analyze FWD deflection data on severely cracked and broken flexible pavements and the differences between the theoretical modelling of fast "workhorse" programs and observed field performance of materials has spurred the development of new concepts with regard to deflection analysis:

1) The function of the "effective modulus of measured surface deflection" or the "effective modulus profile"

2) The tail modulus function, as a quality indicator

3) The profile of the "effective modulus of subgrade deflection", to calculate representative values of subgrade moduli, valid at and around the test load

4) The Non-Continuum - Lateral Discontinuity Index (NLDI), to evaluate the discontinuity of material with regard to lateral dynamic load (shear) transfer (tentative)

5) The Structural Strength Index (SSI), to evaluate the relative structural strength of AC pavements above the mere strength of the subgrade material (tentative)

A computer simulation on a two-layer system has revealed that the deviation of field behavior from elastostatic modelling is not so much due to dynamic influences, but can be better traced to certain properties of layer materials, such as the increase of subgrade stiffness with depth, the presence of an often unrecorded bedrock face and the anisotropy or lateral discontinuity of bonded or unbonded granular materials (with regard to the lateral propagation of impulse load waves from the falling weight in a FWD test).

The aforementioned "effective modulus profiles" can serve as a key to obtain information regarding these items. The new, revised PROBE program is a first attempt to quantify such information by certain parameters (listed in Table 6).

Research should continue to provide a better understanding of the relationship between the effective modulus profile and in-situ average properties of materials and design features, and to provide reliable guidance tables for the indices mentioned above.

Deflections beyond the minimum of the effective modulus profile cannot be used directly to calculate a representative estimate of the subgrade modulus, (only indirectly, via the tail modulus function [3, 4]). If they are used directly, estimates of subgrade moduli may be excessively high. The subgrade modulus must be calculated from deflections closer to the load.

The deflections beyond the minimum effective modulus, however, can be used to provide additional information on the condition of the pavement structure. Other information on pavement condition

is obtained directly through the SSI, and by curve-fitting the points of the subgrade modulus profile adjacent to the test load.

It is recommended to apply the aforementioned new concepts by means of updated versions of the PROBE program and gain experience on a variety of pavement designs and layer materials, in order to calibrate certain parameters of the program. In this research effort, existing FWD data should be used as well as data from special FWD tests to be performed under controlled conditions.

In this step by step revision of the PROBE system it is important to maintain the objective of providing a fast and simple "workhorse" type program which should require less time to run than the duration of FWD testing at one location on the highway.

The Falling Weight Deflectometer is an instrument of high mechanical and electronic quality, in concept and actual design. For the benefit of highway management, it deserves to be matched by a useful and practical interpretation program.

Correlation studies between laboratory tests on field samples and FWD results should be made for both structural layers and subgrade materials

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[1] E.J. Yoder and M.W. Witczak: "Principles of Pavement Design", 2nd Edition, John Wiley and Sons Inc., Page 29.

[2] Per Ullidtz, "Pavement Analysis", Elsevier 1987, Amsterdam

[3] Friedrich W. Jung. "Interpretation of Deflection Basin for Real-World Materials in Flexible Pavements", Research Report RR-242, Ministry of Transportation of Ontario, Canada, 1990.

[4] Friedrich W. Jung, et al. "Testing and Interpretation with the Falling Weight Deflectometer (FWD) in Ontario". A paper presented at the 70th Annual Meeting of the Transportations Research Board, Washington, DC, January 1991, Paper No. 910426.

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[6] D. Stolle, D. Hein, and Y. Wang, "Elastostatic Analysis and Backcalculation Estimates of Pavement Layer Moduli", Roads and Transportation Association of Canada, 1988, C39-C59.

[7] D. Stolle, "Modelling of Dynamic Response of Pavements to Impact Loading", Computers and Geotechnics, 1991, Pages 83-94.

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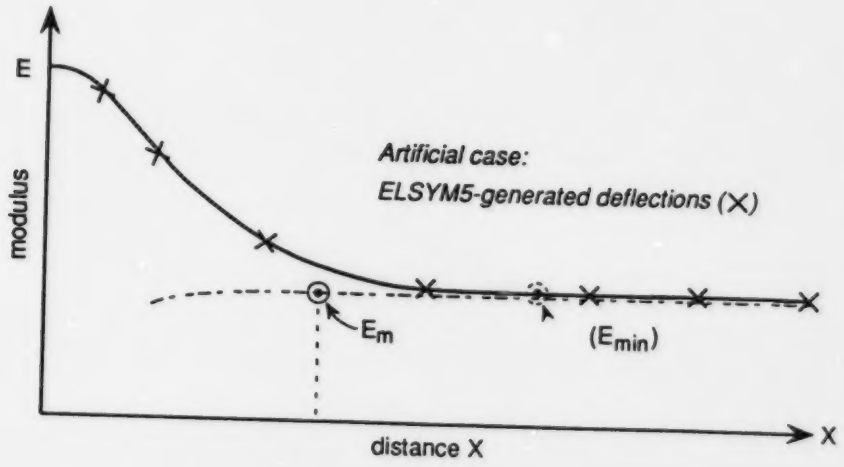


Figure 1/ Effective and tail modulus for elastic layer systems

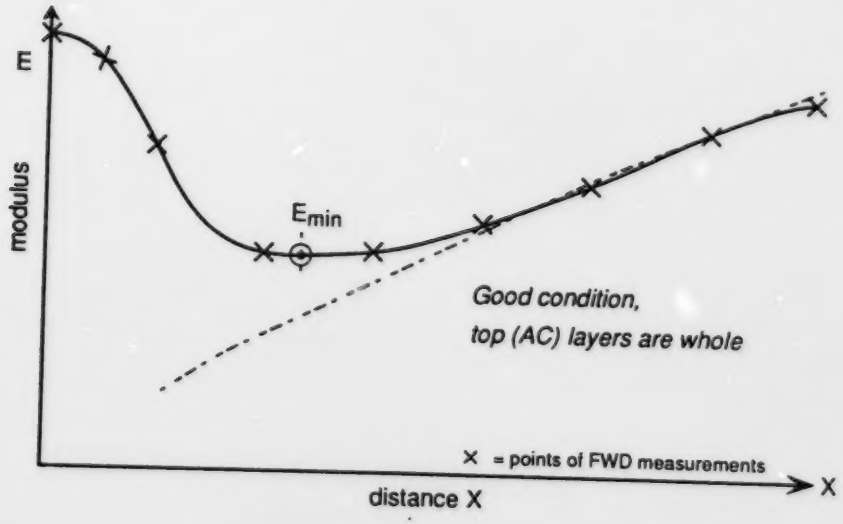
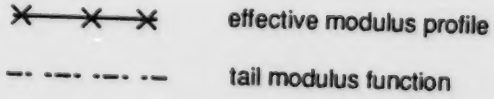


Figure 2/ Effective and tail modulus for whole AC pavements



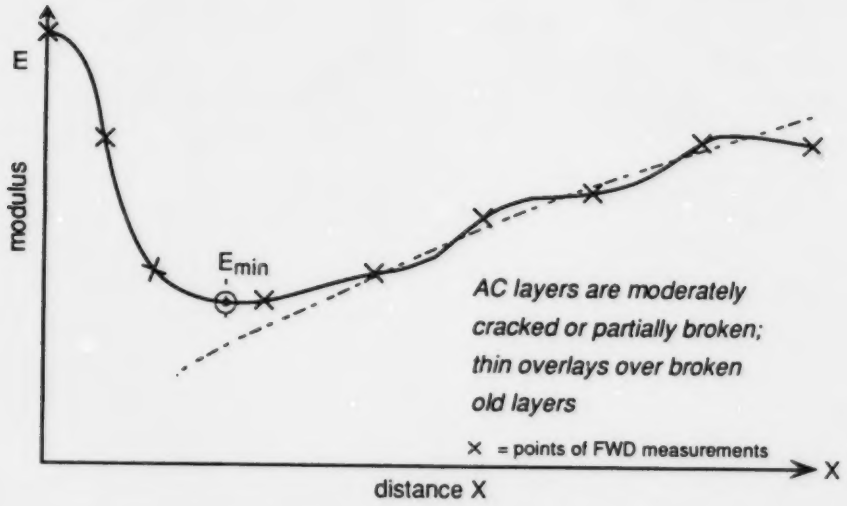


Figure 3/ Effective and tail modulus for cracked AC pavements

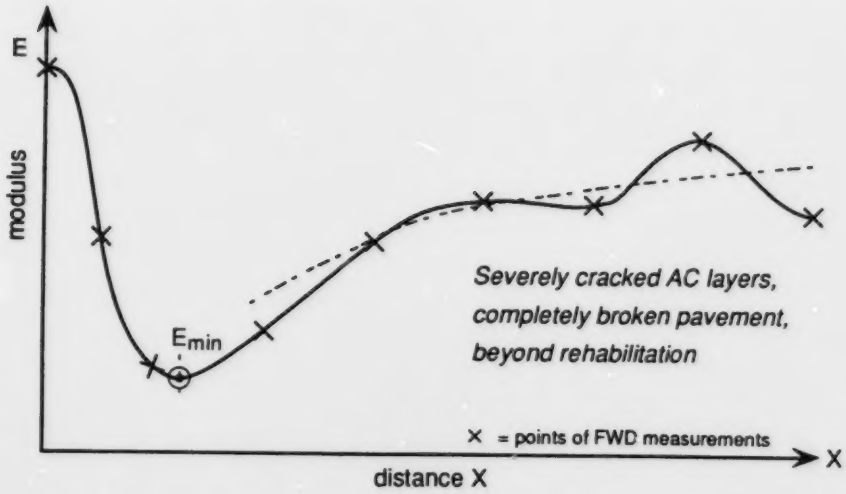
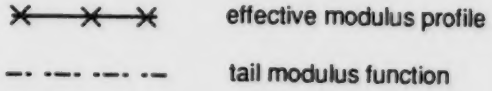


Figure 4/ Effective and tail modulus for broken AC pavements



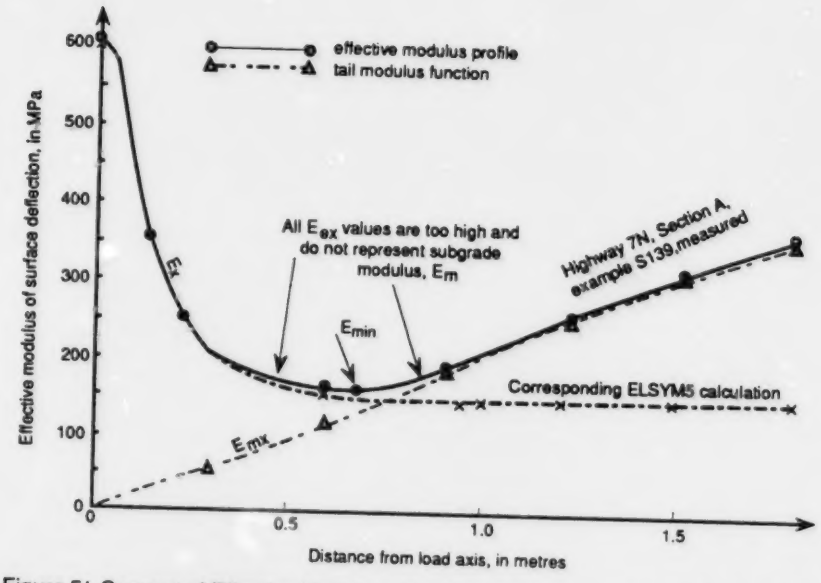


Figure 5/ Concept of Effective Modulus of Surface Deflection, Hwy 7N, Section A Example

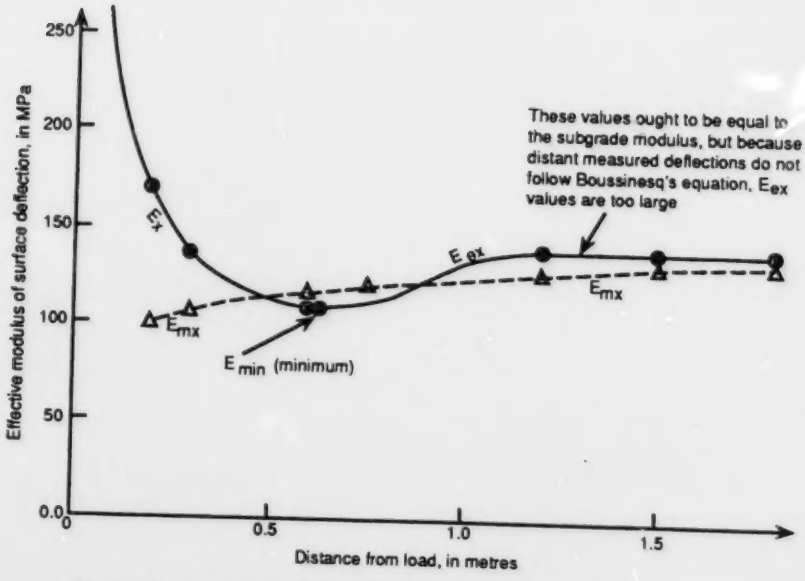


Figure 6/ Concept of effective modulus of surface deflection, Hwy 7N, test pit example, Hwy 80 near Sarnia, 1989, partly broken AC

Effective modulus profile

Tail modulus function

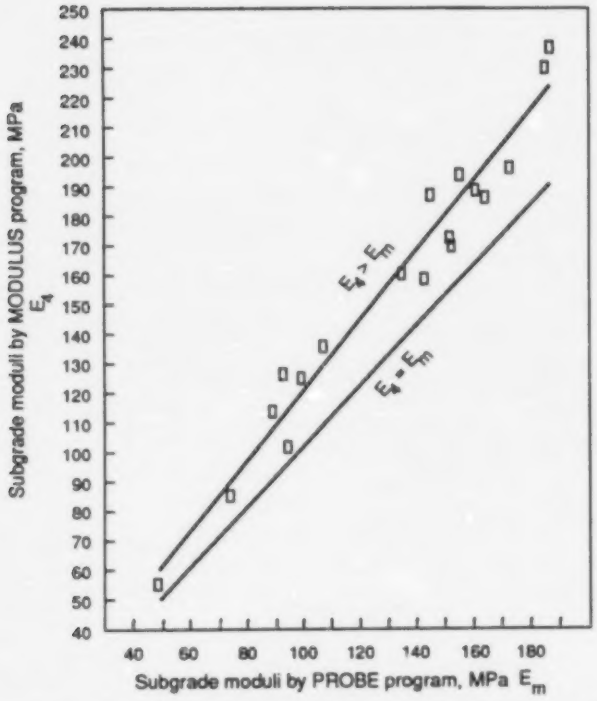


Figure 7/ Comparison of subgrade moduli (21 points, reference (5))

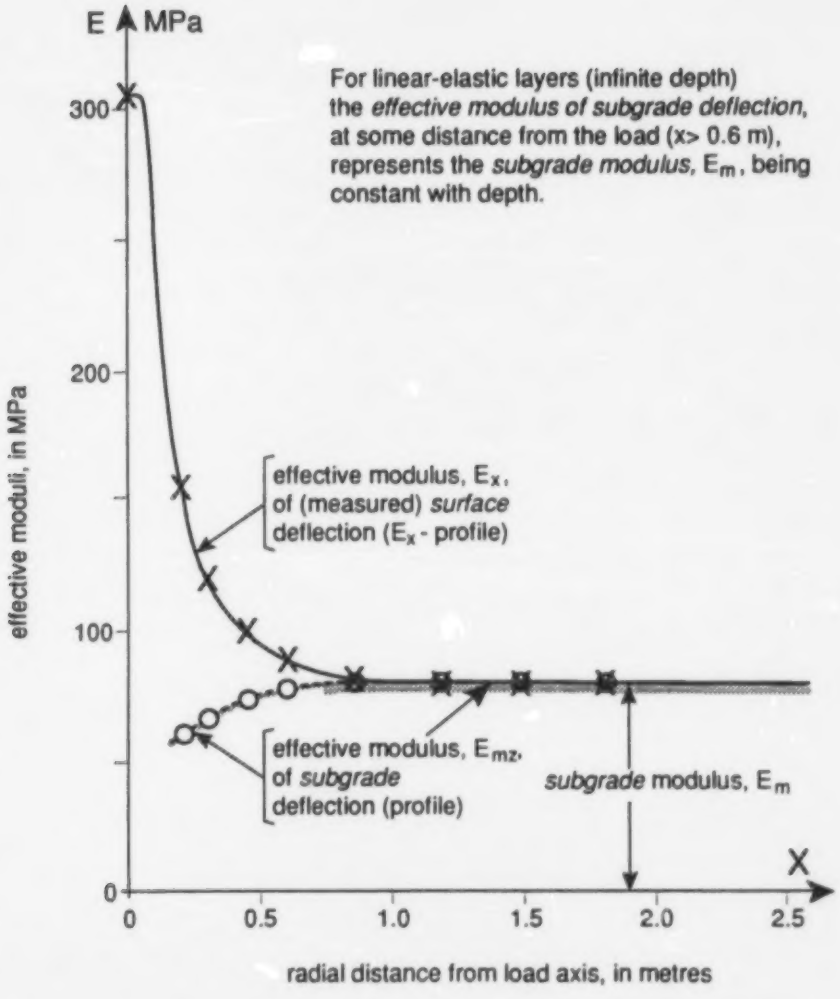


Figure 8/ Linear-Elastic Case, "infinite" depth of subgrade (File: PROF 1)

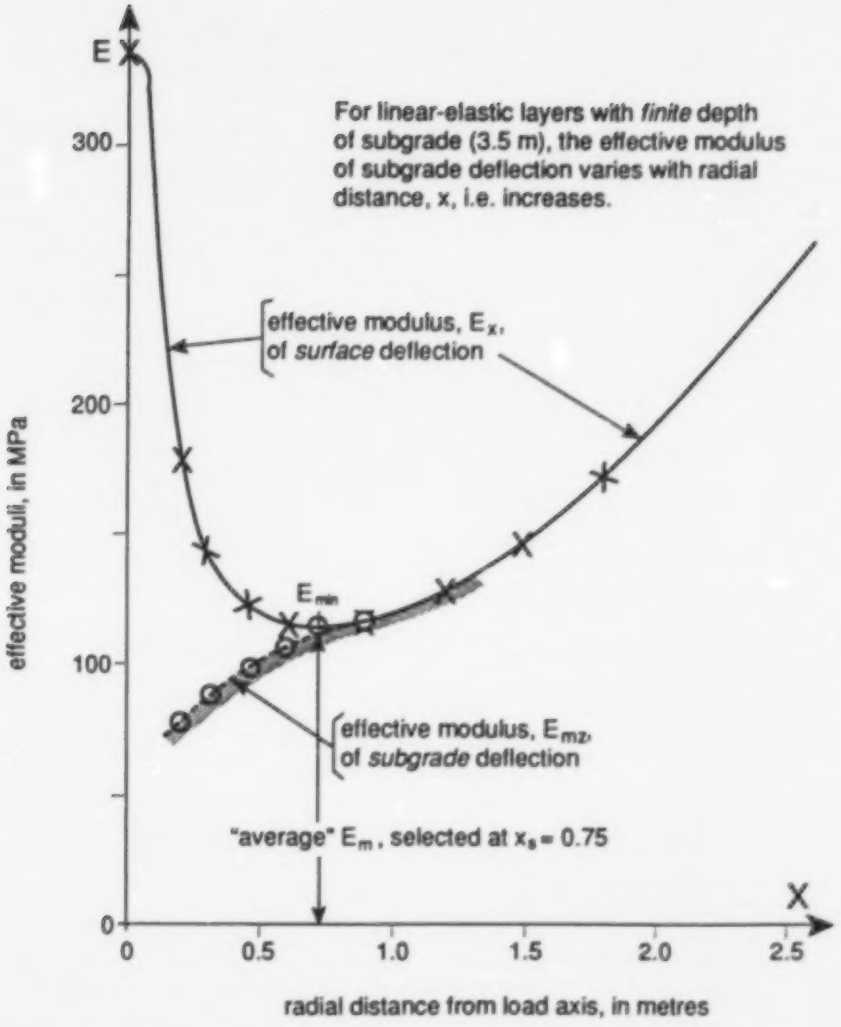


Figure 9/ Linear-Elastic Case, "finite" depth of subgrade (File: PROF 3)

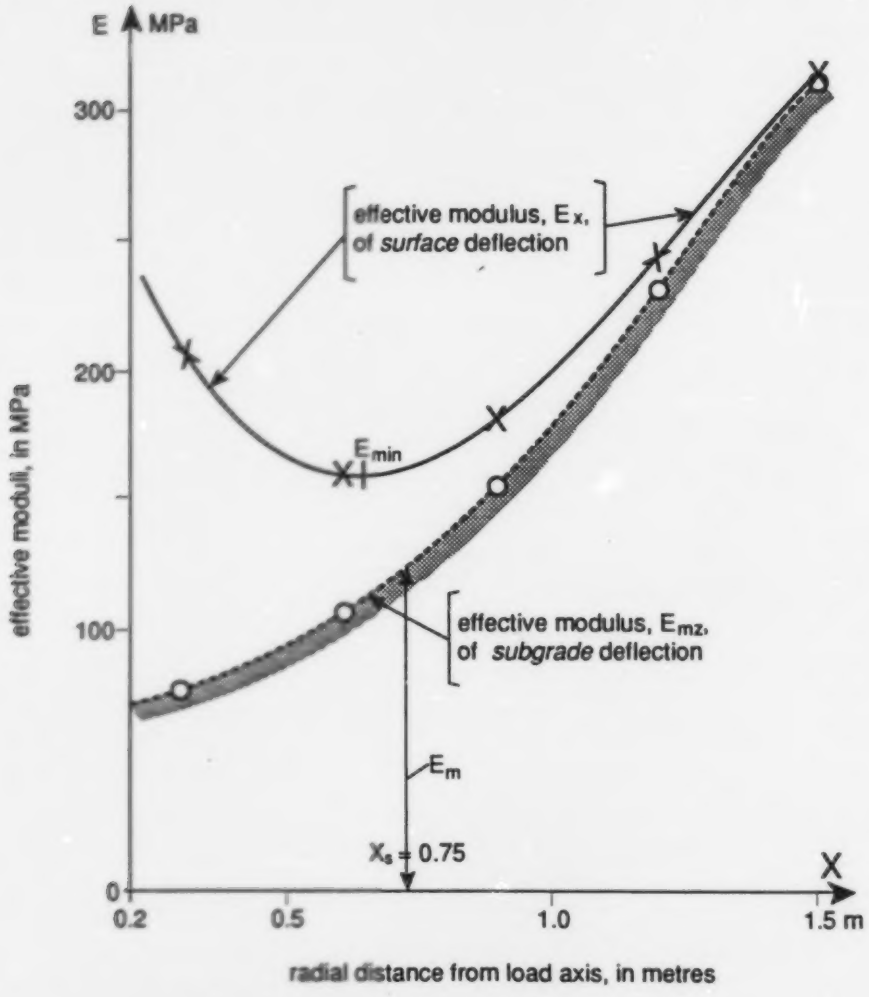


Figure 10/ AC-Pavement in good condition (File: S139)

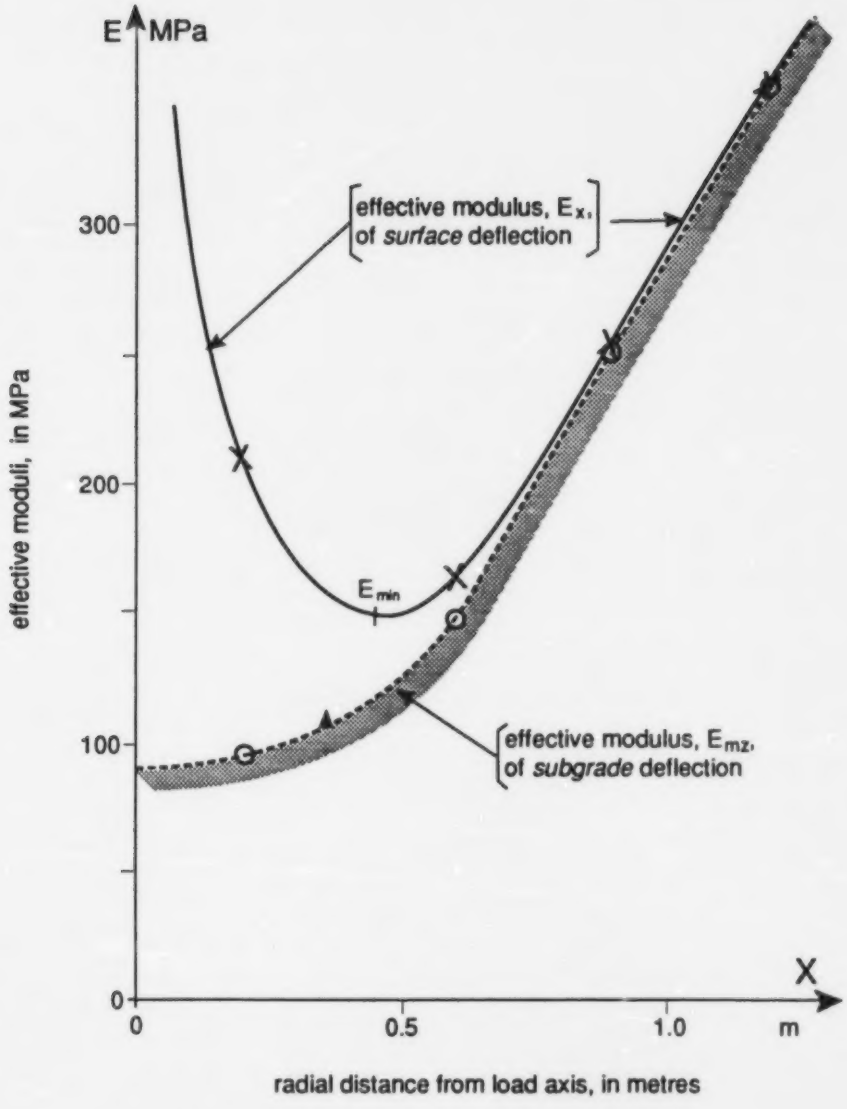


Figure 11/ AC-Pavement cracked and partly broken (File S334)

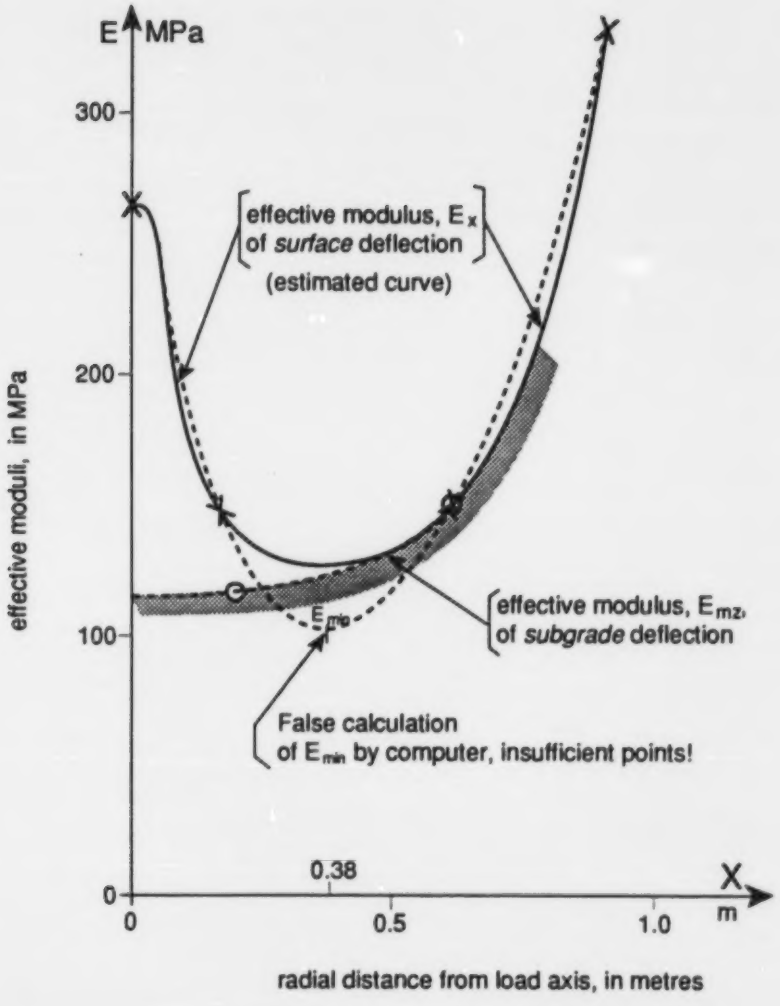


Figure 12/ Broken AC-Pavement, (File S434)

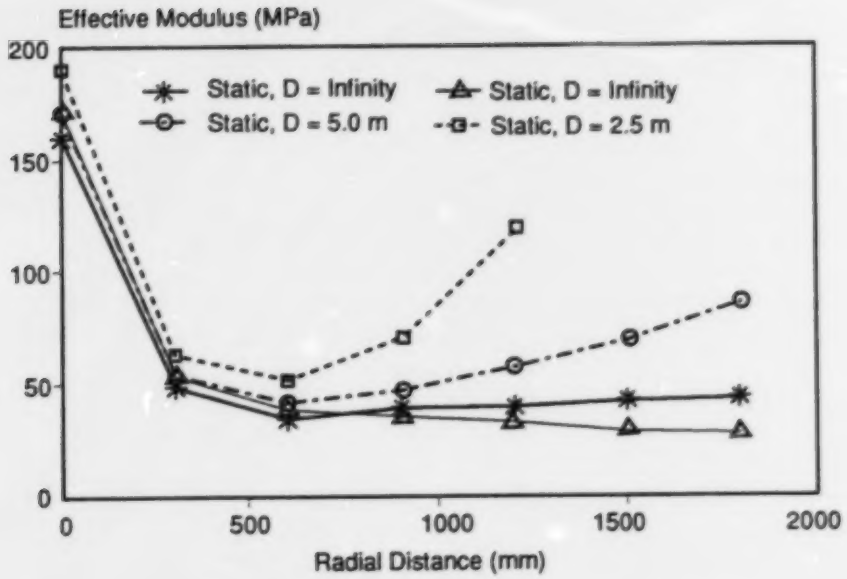


Figure 13/ Dynamic and elastostatic computer simulation

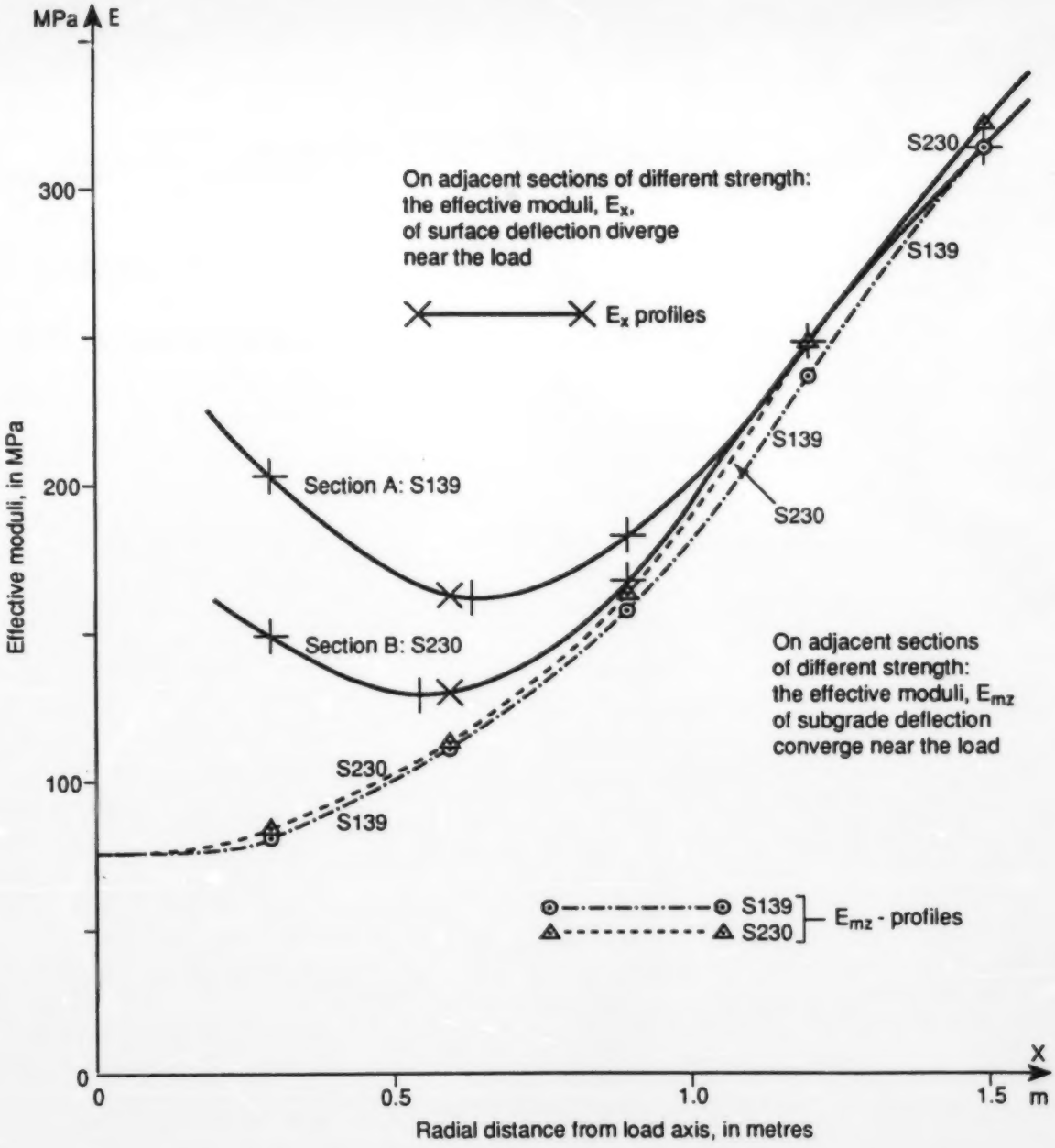


Figure 14/ Effective moduli of adjacent sections